

The Effect of a Superoutburst on the White Dwarf and Disk of VW Hydri as observed with *FUSE*¹

Knox S. Long

Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

Boris T. Gänsicke

Department of Physics, University of Warwick, Coventry CV4 9BU UK

Christian Knigge

Department of Physics, University of Southampton, Southampton SO17 1BJ UK

and

Cynthia S. Froning

*Center for Astrophysics and Space Astronomy, University of Colorado,
593 UCB, Boulder, CO, 80309 USA*

and

Berto Monard

Bronberg Observatory, CBA Pretoria, PO Box 11426, Tiegerpoort 0056, South Africa

ABSTRACT

We have used *FUSE* to obtain a series of thirteen observations of the nearby dwarf nova VW Hyi that cover the period from the end of a superoutburst through the following normal outburst of the system. Here, we present the quiescent spectra taken after each outburst event. The spectra obtained during quiescence contain at least three components. The dominant component over most of the *FUSE* wavelength range is the white dwarf (WD), which cools following the superoutburst. The amount of cooling is dependent on the white dwarf models utilized. For log g of 8.0, the temperature drops from 24,000K just after the outburst to 20,000 K just before the normal outburst. For this model, and for a distance of 65 pc, the radius of the white dwarf is approximately 8×10^8 cm and $v \sin(i)$ is ~ 420 km s $^{-1}$. The fact that the derived radius is smaller than expected for a WD with log g=8 suggests a higher gravity WD or that VW Hyi is somewhat

further than its canonical distance of 65 pc. Either is possible given the current uncertainty (± 20 pc) in the distance to VW Hyi. Earlier suggestions that the WD photosphere show evidence of CNO processed material are confirmed, but our analysis also highlights the fact that significant issues remain in terms of analyzing the spectra of WDs in such unusual physical situations. The second component is relatively featureless and shows substantial modulation on the orbital (and just after outburst, the superhump) period. The second component is most likely associated with the hot spot where material from the secondary encounters the disk, rather than emission from the boundary layer region between the inner disk and WD. This second component fades about 10 days after the superoutburst. There is also a third component, clearly visible in terms of broad emission lines of C III $\lambda 977$, N III $\lambda 991$, and a combination of Lyman β and O VI $\lambda\lambda 1032, 1038$, which appears to be accompanied by a flat continuum. The strength of the emission lines, which are almost surely associated with the accretion disk, appear relatively constant for the duration of the observations.

Subject Headings: stars: novae, cataclysmic variables – stars: individual (VW Hydri) – stars: binaries: close – ultraviolet: stars

1. Introduction

VW Hyi is a very short period SU UMa - type dwarf nova, which lies along a line of sight with extremely low hydrogen column density, possibly as low as $N_H=6 \times 10^{17} \text{ cm}^{-2}$ (Polidan et al. 1990). As discussed by Smith et al. (2006), and as is the case with most cataclysmic variables, its system parameters are not well-known. The system inclination is generally taken to be 60 ± 10 degrees, based on the existence of orbital humps and the lack of eclipses (Schoembs & Vogt 1981). The distance to VW Hyi is thought to be about 65 pc, but this is based solely on the relationship between period and outburst magnitude (Warner 1987, see Sect. 4.1), despite the fact that an astrometric determination should be straightforward today. Smith et al. (2006) have carried out the most recent analysis of the orbital parameters, and for the purpose of this analysis we will follow their lead. They estimate the mass of the white dwarf (WD) to be $0.71_{-0.26}^{+0.18} M_\odot$ (based on the Sion et al.'s [1997] determination of the γ velocity of the WD and their determination of the systemic velocity), which implies a WD radius of $9.3_{-2.6}^{+2.5} \times 10^8 \text{ cm}$ and a gravity of $\log g$ of $8.0_{-0.41}^{+0.38}$, if the mass radius relationship for a C-O WD applies. This and the mass ratio of 0.148 ± 0.08

¹Based on observations made with the NASA-CNES-CSA Far Ultraviolet Spectroscopic Explorer. *FUSE* is operated for NASA by the Johns Hopkins University under NASA contract NAS5-32985

(Patterson 1998) imply a secondary mass of $0.11 \pm 0.03 M_{\odot}$, greater than that expected for a brown dwarf. (See Mennickent et al. 2004, for an alternative view of the nature of the secondary.)

Like other members of the SU UMa group of dwarf novae, VW Hyi periodically undergoes both normal outbursts and superoutbursts. Both types of outbursts occur as a result of a thermal instability that transforms the disk surrounding the WD from a cold, mostly neutral to a hot ionized state. Outbursts occur fairly regularly at intervals of about 20 days, raise the optical magnitude from 14 to 9.5, and last about a day (see, e.g. Mohanty & Schlegel 1995). Superoutbursts are typically separated by 150 days, last of order 12 days, and have a peak magnitude of 8.7.

The actual trigger of superoutbursts is still debated, with the two contenders being the thermal-tidal instability model (Osaki 1989) and the enhanced mass transfer model (Vogt 1983). Analyzing the UV and EUV delay observed during superoutbursts of VW Hyi, as well as the variability of precursor outbursts, Schreiber et al. (2004) concluded that the enhanced mass transfer model provides a better agreement with the observations.

VW Hyi was initially observed at FUV wavelengths with *IUE* (Gänsicke & Beuermann 1996, and references therein) and *Voyager* (Polidan et al. 1990) and has been observed subsequently with *HST* (Sion et al. 2004, and references therein), the Hopkins Ultraviolet Telescope (Long et al. 1996) and, more recently, *FUSE* (Godon et al. 2004). In the high state, spectra of VW Hyi in the *IUE* and *HST* range show blue-shifted absorption lines of N V $\lambda\lambda 1239, 1243$, Si IV $\lambda\lambda 1394, 1403$, and C IV $\lambda\lambda 1548, 1551$, and occasionally P-Cygni like profiles of C IV, superposed on a fairly blue continuum. The spectra, like those of other disk dominated cataclysmic variables, are understood as emission from the disk, modified by scattering in a wind emerging from the disk. In quiescence, VW Hyi is dominated by emission from the WD. Outbursts appear to heat the WD surface, which cools during quiescence. Gänsicke & Beuermann (1996), analyzing all of the *IUE* observations available, concluded that superoutbursts heat the WD from about 19,300 K to 26,400 K, and that the WD cools with a time constant of about $9.8^{+1.4}_{-1.1}$ days. By contrast, Gänsicke & Beuermann (1996) found that normal outbursts heat the WD only to 23,800 K and that the cooling time constant in this case is $2.8^{+1.0}_{-0.5}$ days. In quiescence, the flux near the Lyman limit exceeds that expected from a uniform temperature WD (Long et al. 1996). Godon et al. (2004) conclude the second component in the *FUSE* spectrum resembles that expected from an “accretion belt”, but note its exact origin is uncertain. Godon & Sion (2005) suggest that the emission arises from a region near the boundary layer which also produces the X-ray emission that is seen from the system in quiescence (Pandel et al. 2003).

We have obtained a series of thirteen observations of VW Hyi undertaken with *FUSE*

beginning toward the end of a superoutburst of VW Hyi and continuing through the next normal outburst of the system. The purpose of this series of observations, the most intensive of any cataclysmic variable with *FUSE* (or, for that matter, any satellite since *IUE*) was to better understand the effect of outbursts in a cataclysmic variable on the WD and its implications for the nature of the secondary component in the system. Here we describe an analysis of the spectra obtained in quiescence as well as associated ground-based optical photometry; a detailed analysis of the outburst spectra will be presented elsewhere.

2. Observations and Reduction of the Data

Following notification by Janet Mattei of the AAVSO of the onset of a superoutburst of VW Hyi, the *FUSE* operations staff scheduled a series of 13 observations of VW Hyi (labeled henceforth Observation 01–13). The onset of the outburst was not very well-determined; the system was clearly in superoutburst on JD2453209.8 which triggered the observations. By the time of the first observation, 7.4 days later, the system had declined to m_V of approximately 10.5. A summary of the *FUSE* observations is given in Table 1. The *FUSE* campaign was accompanied by ground-based time series photometry obtained at Bronberg Observatory (CBA Pretoria) during 14 nights spanning the period JD2543221.42–3248.65 (labeled henceforth Observation a–n). The optical data were obtained in white light, using a 30 cm Meade SCT LX200 with an SBIG ST7-XME CCD camera. Data reduction and differential photometry was carried out with AIP4WIN v.1. The spacing of the *FUSE* and ground-based observations, as well as the optical light curve for VW Hyi, as compiled by the AAVSO, are shown in Fig. 1.

A normal outburst of VW Hyi occurred on JD 2453232.7, about 16 days after the system had returned to quiescence. Obs. 11 occurred when the system had a visual magnitude close to that of Obs. 1. Obs. 13 occurred approximately 14 days after this normal outburst; the next outburst appears to have occurred about two weeks later near JD2453259 (based a single observation of the system on that date and a number of upper limits in the interim).

FUSE contains a spectrograph with four independent optical channels that together cover the wavelength range 905 to 1187 Å. The data are recorded in eight segments with overlapping spectral ranges on two separate photon-counting array detectors and are recorded as individual photon events (TIMETAG mode) or as a two dimensional images, summed over a period of order 600 seconds (HISTOGRAM mode). TIMETAG mode is generally preferred, especially for faint sources, because background subtraction in TIMETAG mode is more accurate and because one can choose arbitrary time intervals for constructing individual spectra. All of the VW Hyi observations were obtained in TIMETAG mode, with the

exception of Obs. 2, which was inadvertently obtained in HISTOGRAM mode (but during a time when VW Hyi was fairly bright). All of the VW Hyi observations were obtained through the larger 30" x 30" LWRS aperture, which minimizes, but does not eliminate, slit losses which occur primarily because of thermally-induced misalignments of the optical channels. Moos et al. (2000) and Sahnow et al. (2000) provide a description and overview of the observatory and its performance.

For the analysis reported here, all of the data have been recalibrated using version 3.2 of the “calfuse” pipeline (Dixon et al. 2007). As shown in Table 1, effective exposure times were relatively short in the early observations (3000-6000 s in the first seven observations) and then were increased to 20,000-27,000 s in the last six observations to reflect the anticipated decline in brightness of the source as a function of time from outburst. There were no major anomalies in any of the observations, except the high voltage of the Side 1 detector was turned off for much of Obs. 7 (probably as a result of a single event upset). The standard pipeline products are 8 spectra, one for each optical channel/detector combination, created in intervals chosen by the pipeline. For the analysis which follows, we have constructed average spectra for each observation from these spectra. To account for slit losses, we have renormalized fluxes from the individual spectra so that the average flux near 1060 Å is the same as that of the LiF1B channel, which was used for guiding. In constructing the average spectra, we weighted each data point by the product of the effective area and effective exposure time for that data point. We also used visual inspection to trim the wavelength ranges used for summing the individual channels. Except where noted otherwise the spectra are rebinned from the native wavelength grid (with a resolution of about 0.01 Å), to a resolution of 0.1 Å.

As indicated in Fig. 2, the spectra show an evolution with time. In particular the fluxes decline at all wavelengths from Obs. 1 through Obs. 10, the last spectrum before the normal outburst. The outburst spectrum obtained during Obs. 11 (not shown in Fig. 2) is almost identical both in shape and in flux to that in Obs. 1. The Obs. 12 spectrum obtained about 3 days after the normal outburst has a flux level similar to the last spectrum prior to the outburst, and the last spectrum obtained in Obs. 13 has the lowest flux of all. Declines in flux are accompanied by an overall “softening” of the spectrum, with the fluxes declining more rapidly at 950 Å than at 1150 Å. There appears to be continuum emission down to the Lyman limit in all of the observations, but it is less evident far from outburst than just after outburst.

Not surprisingly, the character of the quiescent spectra are significantly different than those obtained at the end of superoutburst (and during the normal outburst). The Obs. 1 (and 11) spectra show absorption features due most obviously to N IV λ 923, C III λ 977, and

N III λ 991, which are not seen in the short wavelength portion of the quiescent spectra. The Lyman β profile is broader in the quiescent spectra, and the quiescent spectra tend to show O VI $\lambda\lambda$ 1032, 1038 in emission, versus O VI $\lambda\lambda$ 1032, 1038 in absorption in outburst. The emission profiles seen in quiescence are centered near zero velocity and are most likely due to emission from the disk, as is the case WX H_i and SS Cyg (Long et al. 2005). The quiescent spectra also show far narrower and deeper absorption features than seen in outburst. All this is consistent with the hypothesis that the quiescent spectra are due primarily to emission from a fairly slowly rotating WD, while the Obs. 1 (and 11) spectra are dominated by an accretion disk.

3. Short-term UV and optical variability

Our initial inspection of the *FUSE* spectra obtained from the standard data processing did not reveal major variations in the emission properties of VW H_i within individual observations. However, to investigate the ultraviolet time-variability properties more quantitatively, we created time-resolved spectra and light curves using software tools provided by the FUSE Project at Johns Hopkins University, and described in the “IDF Cookbook” (Godard 2004). These data represent the first opportunity to investigate in some detail the short-term variability of VW H_i at ultraviolet wavelengths.

In the following discussion, we assume that VW H_i has an orbital period P_{orb} of 106.950295(20) min (van Amerongen et al. 1987). The accumulated error in the ephemeris of van Amerongen et al. (1987) is $\simeq 0.033$, which is negligibly small in the context of this paper. Following Smith et al. (2006), we apply an offset of 0.15 to the zero-point of the van Amerongen et al. 1987, so that phase zero corresponds to the inferior conjunction of the secondary star,

$$HJD_{\text{max}} = 2\,440\,128.03521(59) \pm 0.074271038(14), \quad (1)$$

i.e. maximum light of the orbital modulation occurs at phase 0.85.

3.1. Optical data

In a first explorative step, we subjected the initial optical data sets, as well as various combinations of mean-subtracted data sets to an ANOVA time-series analysis, which is particularly sensitive to the detection of periodic, but non-sinusoidal variability (Schwarzenberg-Czerny 1996). The morphology of the variability clearly changed between the observations taken before the next normal outburst, and those taken after it. We therefore decided to analyse

the two periods separately.

The ANOVA periodogram computed from the combined observations b–h (Figure 3, top left panel) shows a 1-day alias pattern with maximum power near $\simeq 109.5$ min, i.e. somewhat longer than the orbital period of VW Hyi of van Amerongen et al. (1987). Fitting a multi-harmonic sine wave to the optical data results in $P_{\text{sh}} = 109.4753(76)$ min, and we identify this modulation as the superhump period. Phase-folding the optical data with that period results in a light curve with relatively large scatter (Figure 3, top right panel).

The periodogram calculated from the data pre-whitened with the period obtained from the sine fit above contains again a 1-day alias pattern, now peaking near ~ 107 min (Fig. 3, panel (b)). A multi-harmonic sine-fit to the detrended data results in $P_{\text{orb}} = 106.9312(51)$ min. This value is very close to the the orbital period of VW Hyi measured by van Amerongen et al. (1987), though not formally consistent. van Amerongen et al. (1987) determined the orbital period by fitting a linear ephemeris to times of maximum light in the orbital variation of VVH α i spanning one decade, and did not note any evidence for a period change. The formal discrepancy (3.7σ) between their orbital period and ours is most likely due to an underestimate in the error of our orbital period, based on sine-fitting relatively sparse data. The light curve obtained from folding the optical data pre-whitened with P_{sh} on the ephemeris of van Amerongen et al. (1987) exhibits a double-humped morphology (Fig. 3, right-hand-side panel (b)), as observed in many short-period dwarf novae (e.g. Patterson et al. 1998; Rogoziecki & Schwarzenberg-Czerny 2001; Araujo-Betancor et al. 2005). Maximum brightness occurs near phase 0.85, as expected according to Eq.(1) for an orbital modulation.

For completeness, we also computed a ANOVA periodogram for the combined data set detrended with the orbital period, which shows, as expected, a clear 1-day aliases pattern centered on the superhump period (Fig. 3, panel (c)). Folding the optical data, pre-whitened by P_{orb} , on the superhump period displays a smooth quasi-sinusoidal modulation.

The first optical data set is worth an additional note. Its power spectrum is clearly dominated by the superhump modulation. However, the superhump modulation underwent a phase shift and/or slight period change between observations a and b, which has been observed previously in VW Hyi and other dwarf novae (e.g. van der Woerd et al. 1988), and we hence did not include observation a in the combined data set.

Observations j–n were obtained following the next normal outburst, and we combined them into a single data set for subsequent time-series analysis following the same procedure as above. The ANOVA periodogram computed from these data (Fig. 3, panel (d)) contains an alias pattern with the highest power at $\simeq 107$ min. From a multi-harmonic sine-fit to the data we obtain $P_{\text{orb}} = 106.9421(35)$, i.e. identifying an orbital modulation. The orbital

phase-folded light curve, using Eq.(1), has a similar double-humped morphology to that detected in observations b–h. Maximum brightness occurs again, as expected, around phase 0.85. A periodogram computed from the data pre-whitened with the multi-harmonic sine-fit at the orbital period exhibit no further significant signal.

We conclude that the variability seen in the optical observations following the superoutburst, but preceding the next normal outburst, is dominated by a superhump modulation, but a clear orbital variability is present as well. Following the next normal outburst, the optical light curve of VW Hyi only exhibits an orbital modulation.

3.2. *FUSE* data

As outlined for the optical data above, we first analyzed the individual mean-subtracted *FUSE* light curves, as well as various combinations of individual data sets. Similar to the behavior seen in the optical data, a change in the morphology is observed between the *FUSE* data obtained early after the end of the superoutburst, and data taken somewhat later.

To analyse the variability shortly after the end of the superoutburst, we combined the *FUSE* observations 03–05 (Table 1, Fig. 1). An ANOVA periodogram calculated from these data (Fig. 4, panel (a)) shows maximum power near $\simeq 109.9$ min. A multi-harmonic sine fit to the data results in $P_{\text{sh}} = 109.866(43)$ min, which is marginally longer than the superhump period found from the optical observations. However, as mentioned above, the superhump period and/or phase may drift slightly shortly after the end of the superoutburst.

Next, we combined the *FUSE* observations 08–10. The periodogram computed from these data (Fig. 4, panel (b)) shows an alias pattern with maximum power at $\simeq 106.9$ min, refined to $P_{\text{orb}} = 106.8836(82)$ min from a multi-harmonic sine fit. Folding the data on Eq.(1) produces a double-humped light curve with maximum brightness near phase 0.85, very similar to the orbital modulation seen at optical wavelengths.

A time-series of the *FUSE* observations 12 and 13, taken after the next normal outburst, reveals some marginal power near the orbital period, but the signal-to-noise ratio is too low for any detailed analysis.

We conclude that the variability at ultraviolet wavelengths follows a similar trend as that observed in the optical: whereas the early *FUSE* observations seem to be modulated at the superhump period, the observations taken a few days later are clearly modulated at the orbital period. This implies that we are witnessing an flux component in addition to the emission from the white dwarf which exhibits a strong orbital phase dependence.

This is illustrated in Fig. 5, which shows the wavelength averaged flux from VW Hyi as a function of the number of orbital cycles elapsed since JD 2453217.11732. This time, which is just prior to the beginning of our first observation, was selected so that integral periods correspond to phase 0, given the ephemeris in Eq. (1) corresponding to the inferior conjunction of secondary conjunction, and approximately 0.15 cycles after the maximum brightness of the orbital modulation. There is excess emission in the phase range 0.6 to 1, corresponding to hot spot maximum in these two observations. Similar variability is seen in earlier observations, although the earlier observations cover fewer orbital periods, which makes it harder to identify orbital trends with confidence. The variations are less prominent in Obs. 10, and not apparent in Obs. 12 and 13 in the lightcurves themselves. Except in Obs. 5, peak fluxes are observed near phase 0, that is at hot-spot maximum. The outburst spectra do not show this kind of variability.

Spectra from the high and low flux phases of the Obs. 8 and 9 are shown in Fig. 6. The spectra were created by using the tool “idf_cut” (Godard 2004) which allows one to construct the average spectrum in a phase interval for an entire observation. In this case, we split the data into intervals corresponding to each eighth of a phase. This yielded a total of eight spectra, each corresponding to time-averaged spectra for each eighth of a phase. We then constructed the “high flux” and “low flux” spectra by averaging the three highest flux and the lowest flux spectra, so that “high flux” and “low flux” spectra each contain all of the data obtained over three-eighths of a phase. Specifically, the “high flux” and “low flux” spectra include data from phases 0.625-0.0 and 0.0-0.375, respectively. This method is preferred to splitting the data into a larger number of segments, constructing spectra of the individual segments, and then combining them because, with longer individual segments, the *FUSE* software is able to model the background.

Inspection of Fig. 6 makes it clear that there is a variable continuum component that is much stronger in the “high flux” than in the “low flux” spectrum; the difference spectra are shown in the lower panel of Fig. 6. The general shapes of the difference spectra are similar in Obs. 8 and 9, and in the other observations where phase-dependent flux modulations are observed. This second component accounts for much of the flux below 950 Å, and fills in the flux near Lyman β in the “high flux” spectra. That said, there is no phase interval in which the flux at the center of Lyman β falls completely to zero, as would be expected for a pure WD. This suggests that the “second” component always contributes to some extent (or, more precisely, that there is *some* non-WD component present all of the time). In this regard it is interesting that the spectrum obtained during the low flux phases shows broad O VI in emission; this is usually interpreted as emission from the disk. The second component is not completely smooth, with some evidence of broad absorption at Lyman β and a few higher order Lyman lines, in addition to C III, which is clearly in absorption. There are no

emission features apparent in the second component spectrum.

4. Spectral Analysis

In order to characterize the spectra obtained of VW Hyi in the quiescent interval, we carried out a series of model fits to the data using a large grids of simulated WD spectra calculated with Ivan Hubeny's TLUSTY and SYNSPEC suite of programs (Hubeny 1988; Hubeny & Lanz 1995). Our initial grid, which we have used previously for modelling WZ Sge and U Gem, consisted of model spectra ranging in temperature (T_{wd}) from 10,000 K to 150,000 K (in units of 1000 K below 30,000 K). The grid contains models for atmospheres whose photospheric metal (and He) abundances range from z of 0.01 solar to 10 solar. The grid contains model spectra appropriate for WD rotation rates ($v \sin(i)$) ranging from no rotation to rotation rates of 1200 km s⁻¹ (in steps of 25 km s⁻¹ for the range of relevance for VW Hyi). The grid contains models with gravities ranging from log g=7.5 to 9.0, in steps of 0.5. However, we do not typically attempt to fit the gravity, because there is a strong temperature-gravity degeneracy in the models: one can almost always find a somewhat higher temperature, higher gravity model that fits the data about as well as a given lower temperature, lower gravity model (and vice versa). This is due to higher gravities resulting in stronger Stark broadening of the hydrogen lines, which is compensated by raising the ionization fractions through an increase in temperature. For VW Hyi, the gravity is likely to be around 8.0 (Smith et al. 2006), and, unless otherwise noted, the models we will discuss are for this gravity. Where relevant, we will indicate how the results would change for other gravities.

We used a standard χ^2 fitting routine and fit the entire spectrum, except for those regions near strong interstellar absorption lines and air glow lines. We used the same set of fixed set of wavelength intervals for all of the fits. As is common in our experience with high-S/N spectra obtained with *FUSE* (even with well-understood systems), our fits yielded χ^2_ν that are typically larger than 1. This makes it impossible to directly estimate confidence intervals on the fit parameters via the usual $\Delta\chi^2$ method. There is no straightforward way to deal with this, as the causes of the problem range from poorly understood systematics in instrumental sensitivity or background subtraction, to, in our case, inaccuracies in the atomic parameters that determine the strength of individual lines.

In order to get a handle on the likely uncertainties associated with our fits, we have elected to characterize the errors using the bootstrapping method, see e. g. Press et al. (2007). Briefly, in the bootstrapping method, one fits multiple versions of the data. If the original version of the data set contains N data points, one randomly selects N data points

to fit, allowing individual points to be sampled multiple times to form the new version of the data. One then uses the dispersion in the results to estimate the errors for the parameters in the model. Unless otherwise noted, the errors we quote are 1σ , that is 67% of the trials gave parameter values within the quoted ranges. Real features in the spectra and the models typically have a width of about 3 Å, and hence while the data points within such an interval are formally independent of one another in a statistical sense, any systematic errors in the models (for example due to incorrect atomic data), will affect a region of at least this width. Therefore, in our creation of the bootstrap sample, when we pick a data point for inclusion, we also include all of the "good" data points within 1.5 Å of the original data point.

4.1. The White Dwarf

It should be clear from the discussion of the phase-dependent time variability in Sec. 2 that spectral modeling of the VW Hyi observations will be complex. In general terms, the process we followed was as follows. In fitting the data, we assumed that there is no reddening along the line of sight to VW Hyi, but we did allow for interstellar absorption lines from H and O I, assuming a H column density corresponding to $\log N_H = 18.6$ ²

Primarily to establish a baseline, we began with simple uniform temperature WD models. These models have three variables, T_{wd} , the overall metal abundance z , $v \sin(i)$, and the normalization of the spectrum. The normalization is proportional to the effective solid angle. These models do qualitatively fit many aspects of the data. As expected for a WD with $T_{wd} \simeq 20,000$ K, the models match the general shape of the spectrum, show broad absorption from Lyman β and replicate, at least in a general way, many of the line features in the spectrum. For log $g=8$ models, the derived T_{wd} drops from 27,000 K to 20,000 K from Obs. 2 ($\chi^2_\nu=10.0$) to Obs. 13 ($\chi^2_\nu=5.4$). For Obs. 8, the "low flux" spectrum, that is data between phase 0.0 and 0.375 yields a T_{wd} of 22,000 K with $\chi^2_\nu=3.7$, compared to a value of 24,600K with $\chi^2_\nu=5.6$ for the "high flux" spectrum from phases 0.625-1.0.

There are several problems with this "baseline model", but the obvious one is that it does not account at all for the flux from any extra components, of which the time-variable one is the most obvious. One way to attack this problem is to model the second component

²This value is higher than deduced by Polidan et al. (1990) from *IUE* data and reflects our preliminary curve-of-growth analysis of the column density. Since essentially all of these lines lie in regions excluded from the model fits, χ^2_ν is not affected significantly by this choice. We will present our N_H determination more fully in a future paper discussing the high-state spectra.

as a simple power law, a blackbody, or, as is commonly done, a second synthetic stellar spectrum. In reality, as we have already indicated that there must be at least 3 components, the WD, one associated with the hotspot, and a third associated with the broad emission lines, and so any-two component approach will have its own limitations. In principle we could have added the emission lines explicitly. In practice we have excluded the regions where the emission lines are obvious from the fits.

We have tried all three two-component approaches. As an example of this approach, we describe model fits of the data involving combinations of emission from the WD surface and a second component modeled as a simple power law, e. g.

$$f_\lambda(\lambda) = f_\lambda(1000\text{\AA})(\lambda/1000\text{\AA})^{\alpha-2}. \quad (2)$$

(With this formulation, $f_\nu \propto \nu^{-\alpha}$.)

This produced much better fits than the simpler one-component WD models, both qualitatively and in terms of χ^2_ν for most of the spectra. The results of $\log g=8.0$, scaled-solar abundance, WD plus power law models are summarized in Table 2 for the time-averaged spectra and for the phase-resolved spectra of Obs. 8 and 9. The best fit for Obs. 2 now has T_{wd} of 24,300K and χ^2_ν of 3.6 (compared to 10 previously), while for Obs. 13, T_{wd} is 19,500K and χ^2_ν is 4.2 (compared to 5.4). The combination of WD and power law components produces a much better approximation to the observed spectra, both in terms of fitting the shape of the spectrum near Lyman β as well as providing the correct fluxes near the Lyman limit. Compared to the baseline, pure WD model, the implied values of T_{wd} are smaller by 1,000-2,000 K, and the scaled-solar abundances are larger. Both of these differences are easily understood. The power law component dominates the fitted spectrum near the Lyman limit, and therefore the WD tends to be cooler. The power law component also dilutes the WD portion of the spectrum somewhat even at the longer wavelengths, where the metal lines are most prominent. This is compensated in the fits by increasing the metallicity of the WD component. However, despite these relatively minor differences, the same general trends are still observed as a function of time from outburst, i.e. a cooling of the WD and a gradual decrease in metallicity. Note the the fit including the second component is not only better for the high-flux spectrum from Obs. 8 (χ^2_ν is 2.6, compared to 5.6), but also for the low-flux spectrum (χ^2_ν is 3.1, compared to 3.7), confirming that there is evidence for a second (or third) component even in the low-flux spectrum.

An example of a WD plus power-law fit, the fit to the time-averaged spectrum of Obs. 8, is shown in the upper panel of Fig. 7. The quality of this fit is fairly typical. The overall shape of the spectrum is fit well, and most, if not all, of the features in the data are seen in the model, although not always at the correct strength. The effect of the continuum component is plainly seen in the core of Lyman β and near the Lyman limit. There are some

troublesome regions, however, especially near 1140 Å, where there is a strong feature in the models, which is not present in the data, and also near 1128 Å, where there is a strong feature in the data, which is not present in the model. The 1140 Å feature in the models is due to C II, as one can easily determine by constructing models with lower C abundances while holding other elements fixed. It seems natural to associate the feature at 1128 Å with P V, except that there seems to be little evidence of the stronger component of the doublet at 1118 Å. Over and above these specific difficulties, it is clear that some of the line shapes are not especially well fit. One way to see this is to examine the “errors” on $v \sin(i)$, which are quite substantial in our bootstrapping approach. This basically reflects the fact that the line widths are not consistent with a single $v \sin(i)$ using this model.

The WD plus power-law, WD plus BB, and WD plus stellar atmosphere parameterizations of the quiescent spectra of VW Hyi all result in qualitative and quantitative improvements to the fits, and they do so mainly by fitting the overall spectral shape. In terms of the primary WD component, the results are almost identical, and from a statistical (χ^2_ν) perspective, there is no reason to choose one or the parameterizations over another. We have also carried out similar fits using WD models with different gravities. Again, the results are very similar. The main difference is that best fit temperatures are somewhat higher for higher gravity models. This is a direct result of the fact that at fixed temperature, the Lyman lines deepen as the gravity is increased, but at fixed gravity, they weaken as the temperature is increased.

In order to address some of the problems that remained, we next considered models in which the abundances of various elements in the WD were varied independently. The strongest absorption lines in the spectra are lines of C, N, Si and S, so we created grids of WD models with varying abundances for these elements. We then again fit the observed spectra with a WD plus power-law (or WD plus BB) model. The results were very similar in both cases, and are shown for the log g=8 WD plus power-law model in Table 3. The improvement in the fit can be seen by comparing the fit to the time-averaged spectrum from Obs. 8 in the lower panel of Fig. 7 to the fit shown in the upper panel, in which only the overall metallicity is varied. The models with variable abundances fit the data better in the long wavelength portion of the spectrum (which is where the strongest absorption lines are located and the S/N is highest). Specifically, they improve the fits to Si III complexes near 1110 Å and 1140 Å. One measure of the improved fits to the lines is that the errors on $v \sin(i)$ have dropped by nearly an order of magnitude to 30 km s⁻¹, or about one-tenth of the value of $v \sin(i)$ itself.

The successes and deficiencies of the models appear to be fairly universal, as a comparison of the fits to the time-averaged spectra from Obs. 2 and 13, shown in Fig. 8, reveal.

The fitted value of T_{wd} is 24,100 K for Obs. 2, and 19,000 K for Obs. 13. Both fits require a second component, although the flux at 1000 Å implied by the power law component is an order of magnitude higher immediately after the outburst than in Obs. 13, where there was no evidence of phase-dependent variations. (The underlying shape of the continuum looks a little different, with more emission components near the Lyman limit, near CIII 978, NIII 990, Lyman β , and O VI in the Obs. 13 spectrum.) Both fits describe the overall spectrum fairly well, and the main problem areas have also remained fairly consistent (e.g. near 1195 Å, near 1128 Å, and near 1140 Å).

The improvements in the fits are similar regardless of whether one is considering the “high flux” or “low flux” spectrum of Obs. 8, as shown in Fig. 9. This comparison also reveals a concern, however: in both Obs. 8 and 9, the inferred T_{wd} is hotter in the spectrum from the high-flux state than that from the low flux version. This may indicate that our description for the second component is too simplistic. If so, the difference between the high- and low-state WD temperatures ($\simeq 1000$ K) is an estimate of the systematic error associated with our ignorance regarding the nature of the second component.

The model fits indicate that the abundance of C is about half solar, regardless of time from outburst. A smaller C abundance not only fits the C III lines better, but also reduces the intensity of a C II feature near 1140 Å that has a substantial EW at higher abundances. The abundances of N and Si all appear to be greater than solar in these model fits, whereas S at least after the first week after the end of superoutburst is near solar. There still appears to be a secular trend toward lower metallicity as a function of time from outburst, but it is weaker than for the scaled-solar abundance plus powerlaw fits.

The abundance patterns that are observed in the *FUSE* spectra of VW Hyi are typical of those expected in CNO processed material. Similar N and C abundances have been reported in VW Hyi using *HST* (Sion et al. 2001). Both sets of spectra include C III $\lambda 1176$, which is important in constraining the C abundance, but the N features in the *FUSE* spectra, most notably N II $\lambda 1085$, are disjoint from those observable with *HST*.³ Similar abundance patterns have been reported from spectroscopic analyses of the WDs in some other CVs, including U Gem (Long et al. 2006), and with less precision from analyses of emission line spectra of both magnetic and non-magnetic systems (Gänsicke et al. 2003). The carbon abundances of

³Sion et al. (2001) also reported a large overabundance of P in their analysis of *HST* spectra, which were obtained in early quiescence following a superoutburst, which is interesting in view of the discussion concerning the P V doublet. While our observations were obtained at a similar time in its outburst cycle, we still feel that it is unlikely that the 1128 Å feature is due to P V, both because of the absence of other half of the doublet, and because we have seen the same problem in modeling *FUSE* spectra of other systems, most notably U Gem (Long et al. 2006).

the secondary stars in a number of dwarf novae (but not magnetic CVs) appears to be very low, based on the weakness of the CO bands in the IR spectra (Harrison et al. 2005a,b). The photospheric abundances on the WDs of DNe should reflect that of accreted material from the disk, since metals in a WD quickly sink through the photosphere (Paquette et al. 1986). Indeed, photospheric abundances in the WDs of CVs far from outburst tend to be less than solar, which is thought to reflect the rapid diffusion of accreted material into the interior (Gänsicke et al. 2005). The C abundance of the secondary in VW Hyi has not yet been measured, but one would expect to find that it is also low. The XMM grating spectra of VW Hyi show emission from N VII, but do not extend to long enough wavelengths to include the C lines. Pandel et al. (2003) carried out variable abundance fits to the spectra in the context of a cooling flow; all of the abundances they derived were close to or consistent with solar. Several explanations have been proposed to explain CNO enhanced abundances observed in dwarf novae, including the nuclear evolution of the a secondary star, transfer of CNO material from the primary during the common envelope phase, or pollution of the secondary star with material from nova explosions (Marks & Sarna 1998). (See the discussion for VW Hyi in particular by Sion et al. 2001) The actual cause has not been resolved although the absence of CNO enhancements in the secondary stars of pre-cataclysmic binaries appear to favor the nova hypothesis (Tappert et al. 2007).

Despite the residual problems in the model fits, we believe that the variable abundance models provide a more accurate representation of the system as a function of time than do the simpler models. The apparent trends in T_{wd} , R_{wd} , $v \sin(i)$, and the contribution of the second component are shown in Fig. 10 for $\log g=7.5$, 8 and 8.5 models in which the second component is a power law. The trends are similar when the second component is modelled as a blackbody or a stellar atmosphere. As was the case for the scaled-solar abundance fits, the temperatures for $\log g=8$ are lower by about 2000K than for $\log g=8.5$, which causes the apparent radius for $\log g=8$ to be about 25% higher than when $\log g=8.5$ is assumed. For fixed gravity, the derived radius is fairly constant with time.

Based on the standard Hamada & Salpeter (1961) relationship, the expected radius for a “cold” WD is 11.9×10^8 , 8.9×10^8 and 6.3×10^8 cm for $\log g=7.5$, 8, and 8.5 respectively, while the more realistic Bergeron et al. (2001) models, which account for the finite temperature of the WD, yield 12.9×10^8 , 9.1×10^8 and 6.3×10^8 cm. Both relationships are shown in Fig. 11, and compared to radii derived from the variable abundance WD plus power law fits. The average radius (taken from the time-averaged observations more than 5 days from superoutburst and excluding Obs. 10) for an assumed distance of 65 pc is 10.1×10^8 , 8.0×10^8 and 6.3×10^8 cm for $\log g=7.5$, 8 and 8.5 respectively.⁴ This comparison favors \log

⁴It is clear from Table 3 that the fitted normalizations in the high and low flux phases of Obs. 8 and 9

$g=8.5$ and a mass close to $0.93 M_{\odot}$, slightly higher than the values of $8.0^{+0.38}_{-0.41}$ and $0.71^{+0.18}_{-0.26} M_{\odot}$ suggested by Smith et al. (2006). However, the results based on our spectral fits depend on the assumed distance. If VW Hyi is at 74 pc, rather than 65 pc, our results and those of Smith et al. (2006) can be reconciled.

A distance of 74 pc is certainly within the allowed distance range for VW Hyi, since as we noted earlier, the current distance estimate is based only on the relationship between outburst magnitude and orbital period. To verify this assertion, we re-estimated the distance to VW Hyi using the latest calibration for the inclination-corrected $M_{V(max)}$ - P_{orb} relationship for normal dwarf nova outbursts provided by Harrison et al. (2004), which agrees very well with the Warner (1987) relationship in the period regime appropriate to VW Hyi. We found $d = 65 \pm 20$ pc. This estimate includes the usual inclination correction, and the quoted uncertainty accounts for both the 0.5 mag scatter in the relation (see Harrison et al. 2004) and the 10 degree error on the inclination of VW Hyi. For comparison, a lower limit of 50 pc is obtained by assuming that the system harbours a non-degenerate secondary which follows the semi-empirical donor sequence of Knigge (2006) and dominates the 2MASS K-band flux.

The value derived for $v \sin(i)$ and $F_{\lambda}(1000 \text{ \AA})$ for the second component are not dependent on the adopted $\log g$. The rotation velocity of the WD, $v \sin(i)$, appears to be somewhat higher immediately after the outburst, perhaps 500 km s^{-1} , before settling to a value of about 420 km s^{-1} after 5 days. Similarly, $F_{\lambda}(1000 \text{ \AA})$, which effectively represents the residual flux at the base of Lyman β declines rapidly during the first 10 days after the outburst and is approximately constant after that time. It never disappears entirely, however. We will return to the question of how these results should be interpreted in Sec. 5, below.

4.2. The spectrum of the time-variable component – the Hot Spot

It is hard to imagine how the phase-dependent component seen in the spectrum of VW Hyi following the superoutburst can be associated directly with the WD, especially since this component peaks at the same orbital phases where the optical light peaks. It seems much more likely that this emission is due to a physically separate source, associated with the hot spot. Simple black body fits to the difference spectra constructed from the high-

differ from the normalization measured in the time-averaged spectra by about 10%. This translates to an uncertainty in the radius of about 5%. However, the normalizations derived for the later observations, when there was no time-variable component agree with those in Obs. 8 and 9, when the phase dependent time variations were evident.

and low-state spectra in Obs. 8 and 9 yield temperatures of 18,900 K (Obs. 8) and 19,600 K (Obs. 9) and apparent luminosities of 9×10^{31} ergs s $^{-1}$. This is very close to the luminosity of the WD at these times. The characteristic size of the BB emitter inferred from these fits is comparable to, or somewhat larger than, that of the WD, i.e. 10 9 cm. While the exact size depends somewhat on the geometry assumed, as well as on the isotropy of the emitted radiation, it is clearly much smaller than the size of the accretion disk ($\simeq 10^{10}$ cm).

A BB spectrum does not model the observed difference spectra very well. As indicated in Fig. 6, the problems are not simply the overall spectral shape but also evidence for a broad absorption near Lyman β and a narrow feature due to C III $\lambda 1176$. This suggests modeling in terms of stellar atmospheres. In order to see if this was an improvement over a BB, we created a small grid of model spectra with solar abundances and various gravities ranging from log g=4 to log g=8. Initial tests showed that the fits were insensitive to $v \sin(i)$, mainly because the S/N in the difference spectra makes it impossible to identify narrow features. We therefore smoothed the difference spectra to a resolution of 0.5 Å for the purposes of these fits. A comparison of the best fit for log g=4 is shown in bottom panel of Fig. 12. For log g=4, the best-fit temperature was 25,000 K for both Obs. 8 and 9. The isotropic luminosity and size scale are smaller than for the blackbody fits, averaging about 2.5×10^{31} ergs s $^{-1}$ and 3×10^8 cm for the two observations. The temperature and size of the emitting region depend upon the assumed gravity. For log g=8, which is less justifiable from a physical perspective than log g=4, the fitted temperatures are higher, $\sim 40,000$ K and the sizes are smaller, 1.1×10^8 cm. The difference in temperature is an indication of how much the gravity affects the spectrum of a star in the FUV in this temperature range. However, the luminosity is not very dependent on the assumed gravity, averaging 2.5×10^{31} ergs s $^{-1}$ for log g=8. The model fits using stellar atmospheres are better fits than the simple blackbody fits, both qualitatively and in a χ^2_ν sense, but, clearly, from a physical perspective they should still be viewed with caution.

Nevertheless, if 25,000K is a reasonable estimate for the temperature of the hot spot emission region observed with *FUSE*, it is easy to show that this emission region does not contribute very much to the optical emission from the hot spot. More specifically, our 25,000 K hot spot would produce a flux of only about 7×10^{-16} ergs cm $^{-2}$ s $^{-1}$ Å $^{-1}$ in the visible. By contrast, the amplitude of the optical modulation (approximately half a magnitude at m_v of 13), corresponds to an optical hot spot flux of 9×10^{-15} ergs cm $^{-2}$ s $^{-1}$ Å $^{-1}$. Thus the optical hot spot emission must arise from a larger region emitting with a cooler effective temperature. We do not have enough information to accurately measure the temperature of the optical hotspot, and indeed there have been few efforts to determine conditions in the physical conditions in the hot spot. The existing estimates of hot spot temperatures in other systems, which are largely based on broad band optical colors, are in the neighborhood of

10,000 to 15,000 K (Warner 1995, and references therein). For VW Hyi, these temperatures and the observed magnitude variation, would imply luminosities for the optical hot spot of $4 - 9 \times 10^{31}$ ergs s $^{-1}$, comparable to, or slightly larger than, the luminosity of FUV hot spot.

4.3. A third component to the spectrum - disk emission

Orbital variations in the flux from VW Hyi become far less apparent after Obs. 9 and do not reappear after the normal outburst of the system. However, a uniform temperature WD does not account for all of the emission from the system in the FUV, even in Obs. 13. This is illustrated in Fig. 13, The upper and lower panels of this figure show the Obs. 8 “low flux” spectrum and the Obs. 13 time-averaged spectrum with the variable abundance WD model fit subtracted from the spectrum. Ignoring the narrow air glow lines, these spectra are characterized by broad emission features of C III $\lambda 977$, N III $\lambda 991$, and a combination of Lyman β and O VI $\lambda\lambda 1032, 1038$. These WD-subtracted spectra also show a continuum (broken by some absorption features that may reflect imperfections in the WD models; see discussion above) which clearly rises towards the Lyman limit, probably due to emission from the higher-order Lyman lines. The flux associated with this spectrum does not vary greatly between Obs. 8 and 13, i.e. from 6 to 30 days after the superoutburst, a fact which is also evident from the fitted fluxes at 1000 Å in the variable abundance fits included in Table 3. In the earlier observations, it is difficult to separate out the continuum associated with this portion of the spectrum from that associated with the hot spot, since we do not have good phase coverage. However, what is clear from simple inspection of the data is that the flux in O VI $\lambda\lambda 1032, 1038$ is not very different in Obs. 2 and 13, so the emission line portion of the third component is relatively constant over a period from just after superoutburst and through the normal outburst.

The same third component we have identified here was also apparent in the *FUSE* spectrum of VW Hyi that was analyzed by Godon et al. (2004). Moreover, the same emission lines are seen in some other CVs in quiescence, including SS Cyg and WX Hyi (Long et al. 2005), and resonance lines of N V $\lambda\lambda 1239, 1243$, Si IV $\lambda\lambda 1394, 1403$, and C IV $\lambda\lambda 1548, 1551$ are commonly seen in the wavelength range covered by *IUE* and *HST* (Mauche et al. 1997). Although the emission lines that are seen in the optical spectra of SS Cyg and other systems are likely to be associated with the disk and have been reproduced in simulations of disk spectra (Williams 1980; Kromer et al. 2007), the temperature from a standard steady state disk is too low to produce emission from lines like C IV $\lambda\lambda 1548, 1551$ or, especially, O VI $\lambda\lambda 1032, 1038$, since the disk is thought to be relatively cold (<6000 K) in quiescence. The broad emission lines seen in the UV most likely arise in a chromosphere above the sur-

face layer of the disk. Fits to the profiles indicate that the resonance lines, such as C IV $\lambda\lambda 1548, 1551$, have surface fluxes in the lines that fall off approximately as r^{-2} (Long et al. 2005). The physical mechanism driving a corona or chromosphere has not been conclusively established. Shaviv & Wehrse (1986) suggested it could arise from viscous effects in the upper layers of the disk. However, Ko et al. (1996) showed that they could reproduce the line fluxes of a number of systems assuming a corona generated by X-ray illumination of the disk and favored this over viscous dissipation effects in the upper atmosphere. A re-examination of both of these hypotheses is in order today, given the existence of a fairly large number of high SN, high resolution *HST* spectra and the existence of more detailed theories of the interaction between the X-ray gas and the inner accretion disk (e.g. Meyer et al. (2000)). However, the *FUSE* observations of VW Hyi do not provide the ideal set of data to investigate this, since the spectra are dominated by other spectral components. Nevertheless, if the FUV emission lines do arise in the disk, it is quite likely that the rest of the third component spectrum can be explained away as emission from weaker lines, plus possibly some continuum emission from the disk corona. There is no compelling reason to associate it with the boundary layer, if by the boundary layer one means a localized structure at the interface between the accretion disk and the WD.

5. Discussion

When the disks in dwarf novae transition into the outburst state, the WD is buffeted by the effects of radiation and increased mass transfer onto the WD surface. In the case of VW Hyi, this buffeting lasted about 9 days and heated the WD by at least 5,000 K. The WD was far less affected by the much shorter normal outburst that occurred prior to Obs. 12. Similarly, the outburst appears to have buffeted the secondary as well, as evidenced by the fact that the hot spot was considerably brighter after the outburst than previously, resulting in a hotter and more extensive hot spot that even affected the FUV emission. The effects of the normal outburst on the secondary were clearly much weaker.

The temperature evolution of the WD in VW Hyi was shown in Fig. 10. The luminosity of the WD component in the spectrum is shown in Fig. 14. Just after the outburst, the luminosity of the WD was about 1.7×10^{32} ergs s $^{-1}$. It then declined by almost a factor of 3 by the time of the last observation with *FUSE*. The decay was approximately exponential, with a time constant of about 7 days. If L_{wd} at Obs. 2 is interpreted as the quiescent luminosity, then the luminosity excess was 1.1×10^{32} ergs s $^{-1}$. These results are very similar to the results obtained by Gänsicke & Beuermann (1996) based on a collection of *IUE* observations of VW Hyi (even though the *IUE* data did not allow a clean separation of the WD from the

other components in the emission spectrum). Gänsicke & Beuermann (1996) found a higher temperature of 26,400 K than we did here just after outburst, and this may be due to the effects of other continuum components. Had we neglected the other components in our analysis, we would have derived temperatures that were higher by several thousand degrees just after superoutburst. But it could also be that the superoutburst we observed was somewhat shorter than the typical superoutburst. Either of these effects could also explain why the time constant for WD cooling we derive – 7 days – was somewhat shorter than the value they derived, which was $9.8^{+1.4}_{-1.1}$ days.

Three closely related explanations have been suggested for the temperature evolution of a WD in a CV in the aftermath of an outburst. The first concentrates on the altered state of the WD after the outburst. More specifically, the outburst heats the surface layers of the WD, and, once the outburst ceases, the WD radiates away the thermal energy that was deposited. The outburst also deposits material on the surface. Even if this material were deposited on the photosphere at the photospheric temperature, it would still leave the WD out of equilibrium structurally. Once the outburst ceases, the surface layers are able to radiate the thermal energy that was deposited and, over longer time scales, the WD will readjust its internal structure to reflect its increase in mass (Sion 1995; Piro et al. 2005). The fact that WDs in CVs accrete and grow in mass (at least between nova outbursts) explains why they are hotter than isolated WDs of comparable age (Townsley & Bildsten 2003).

The second explanation for WD heating was advanced by Long et al. (1993), who suggested that departures from single temperature WD fits to the HUT spectrum of U Gem in quiescence could be explained if the outburst spun-up a surface layer of the WD and the slow conversion of rotational energy to heat produced a gradually decaying apparent temperature for the WD. Two component WD fits to the quiescent spectra of several DNe, including VW Hyi, have been carried out, and do produce improvements in the statistical quality of some of the fits. Generally speaking, as in the case of VW Hyi (Sion et al. 2001), the second component appears to be stronger just after an outburst and to rotate more rapidly than the primary component. One of the arguments for this hypothesis has been that it helps to explain away a troubling problem for single temperature fits in U Gem, which was that the radius of the WD appeared to evolve with time from outburst. However, despite the fact that two-component WD fits produce lower χ^2_ν , this is not strong evidence for the physical reality of a rotating region of the WD, especially given our increased awareness of multiple components in the FUV spectra of quiescent CVs. For example, it is easy to demonstrate the same improvement in χ^2_ν can be achieved with a model consisting of the WD and a power law. To assert physical reality, one needs clear evidence of more rapid rotation in the higher ionization state lines or in the FUV portion of the spectrum. Although VW Hyi clearly has multiple components in its spectra, there is no “smoking gun” for a second component

with a spectrum resembling a rapidly rotating, hotter region of the WD, or indeed any other component, such as an inner accretion disk ring, with a different temperature from the WD. Furthermore, Piro et al. (2005) has recently investigated this possibility that rapidly rotating belts exist in the WD surface layers, concluding that although they may exist, they are unlikely to be as important as compression heating in explaining the cooling time of the WD.

The third scenario for explaining the time evolution of the WD spectrum posits that the accretion rate is still elevated at the end of the optical outburst and that the T_{wd} is elevated by this accretion. There is some theoretical basis for this. In particular, Meyer et al. (2000), partly to explain the fact that X-ray outbursts of DNe are often delayed from the optical outbursts, proposed that accretion onto the WD in quiescence proceeds via a coronal flow from the disk onto the WD, and that the coronal flow erodes the inner portions of the quiescent disk, leaving a hole in the inner disk. As described by Mineshige et al. (1998), the hole steadily expands toward larger radii in quiescence and the mass accretion rate (see their equation 4) onto the WD drops with time. If this is the case, then both the X-ray measured accretion rate and possibly the WD temperature should drop with time. Observationally, van der Woerd & Heise (1987) observed VW Hyi for an extended period in 1986 and concluded the X-ray flux declined slowly by a factor of 1.2-1.6 during the inner outburst period, which they linked to a decline in the mass accretion rate. Pandel et al. (2003) used XMM to observe VW Hyi in mid-quiescence and showed that the X-ray emission lines which dominated the X-ray spectrum may be rotating at the velocity of the WD, but not at the velocity of the inner accretion disk. They also found that short term variations in the X-ray flux lag short term variations in the 2400-3400 Å flux by about 100 seconds. They modeled the emission in terms of a cooling flow onto the WD surface from the disk, all of which is generally consistent with the picture proposed by Meyer et al. (2000). Liu et al. (2008) have recently modeled the X-ray spectrum of VW Hyi quiescence in terms a hot tenuous coronal inflow, concluding that one can obtain good fits to the data, but only if the conductivity of the plasma is low.

To our knowledge, no one has actually attempted to calculate the heating of the WD due to a coronal flow. That said, it seems unlikely that ongoing accretion in VW Hyi plays the dominant role in the temperature evolution of the WD, mainly because the required accretion rate is so substantial. There is very little evidence for such a large accretion rate from the inner disk in quiescence, or just after the return to quiescence. Based on STIS spectra of VW Hyi, Merritt et al. (2007) estimate the accretion rate in the inner disk to be $\sim 4 \times 10^{-9} M_\odot \text{yr}^{-1}$, assuming M_{wd} of $0.8 M_\odot$ and a distance of 65 pc. We plan, as noted earlier, a full discussion of the *FUSE* outburst spectra later. However, following a procedure essentially identical to that of Merritt et al. (2007), we derive a mass accretion rate

\dot{m}_{disk} during Obs. 1 of about $0.9 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$, which corresponds to a disk luminosity of $3.4 \times 10^{33} \text{ ergs s}^{-1}$. Our accretion rate is lower because the flux from VW Hyi was lower than in the observations described by Merritt et al. (2007). If one wished to attribute the excess luminosity of the WD during Obs. 2 to instantaneous heating of the WD by the ongoing accretion, one would need the accretion rate to be at least 0.75% of that observed at outburst maximum, or 3% of the rate when measured during Obs. 1, that is $2.7 \times 10^{-11} M_{\odot} \text{ yr}^{-1}$. This would have to be mostly hidden, since the accretion rate at the inner boundary reported by Pandel et al. (2003) from XMM at mid-quiescence was far less, namely $8 \times 10^{-14} M_{\odot} \text{ yr}^{-1}$. It is interesting that the overall abundances that we measure in VW Hyi are higher than in some other dwarf novae, which might indicate the accretion rate is higher than normal. But the absence of significant and continuing decline in the abundances with time from outburst suggests that the accretion rate is not varying dramatically. In principle, given an accretion rate and the abundances of the accreting material, one should be able to calculate the photospheric abundances, but this calculation has also not, to our knowledge, been carried out.

It is interesting in this regard that the time scale associated with declining emission from the hot spot observed optically and with FUSE in VW Hyi is similar to the WD cooling time scale. The mass transfer rate from the secondary to the hotspot, given a luminosity of $1 \times 10^{32} \text{ ergs s}^{-1}$ is about $2 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$ (see, e. g. Warner 1995, to obtain this estimate). Thus, if a portion of this material could make its way to the WD, it would provide a source of heating.⁵ The Doppler maps of the VW Hyi in quiescence obtained by Smith et al. (2006) do show that emission from the stream is extended in the region between the stream trajectory and its so-called “Keplerian shadow” of the stream, but do not appear to show heated disk material at the WD. Hydrodynamic simulations of stream disk interactions (e. g. Armitage & Livio 1996) show material ricocheting off of the stream impact region to significant heights above the disk, and extending toward smaller radii. But, ultimately, this material is entrained in the disk, and does not end up on the WD. As in the case of the coronal flow picture developed by Meyer et al. (2000) and recently described by Liu et al. (2008), it is not clear how this material could remain undetected in X-rays. Our view is that it will be very difficult to establish that strong, ongoing accretion onto the WD is occurring in VW Hyi through studies of WD cooling, since the short interoutburst period limits the baseline for such studies. However, Godon et al. (2006) have argued that ongoing accretion is required to explain the cooling of the WD in WZ Sge, which exhibits far more infrequent

⁵As we noted earlier the luminosity of the hot spot and of the WD are similar. This, however, is completely coincidental. If the accretion rate onto the WD were similar to that of hot spot, then the WD would have a temperature of order 60,000K, which is ruled out by the observations.

outbursts than VW Hyi.

There have also been a number of suggestions that the boundary layer might be present in the UV spectra of DNe, including VW Hyi. Godon & Sion (2005) present a recent summary of the case for this in VW Hyi. They point out that a number of studies with *HST* and *FUSE* have concluded that a non-WD component contributes to the quiescent spectrum of VW Hyi. They also note that when this component is modelled with WD spectra, it typically yields a higher temperature and faster rotation speed than the actual WD component. Godon et al. (2004), in particular, analyzed a spectrum obtained with of VW Hyi obtained 11 days after a normal outburst and concluded that the non-WD component had a temperature of 50,000 K and $v \sin(i)$ of 3000 km s^{-1} , similar to the Keplerian velocity in the inner accretion disk. We agree that there is a very evident non-WD component in the spectrum analyzed by Godon et al. (2004) (indeed this was one of the motivations for carrying out the present study). We have re-examined this spectrum, and checked, in particular, whether there was any evidence of orbital modulation; there was not. Interestingly, the spectral shape of the non-WD component in this spectrum seems to resemble the spectral shape of what we have called the third component in our spectra, i.e. relatively flat with a rise in flux towards the Lyman limit. However, this component is much brighter in the Godon et al. (2004) spectrum than in our spectra following the normal outburst (e.g. Obs. 13). Godon & Sion (2005) assert that it seems likely to them that this component is the boundary layer and that this component provides 4/5 of the boundary layer luminosity.

Our view, on the other hand, is that the data do not constrain the origin of this component of the spectrum, because, except for the emission lines, which arise from a substantial portion of the disk, the spectrum of what we have called the “third component” is relatively featureless. In order to establish that the continuum arises from the boundary layer, one needs to show observationally that it is not associated with the disk, or at least show that the emission lines can be produced without producing an associated continuum, or pseudo-continuum of other lines.

Finally, it is clear to us that a precise definition of what one means by boundary layer emission is sorely needed. This definition needs to distinguish direct emission from the boundary layer from various forms of reprocessed emission, including a coronal surface layer on the surface layer of the disk. In the absence of such a definition, it will be difficult for observers and theorists to reach consensus on the nature of the multiple components in the spectrum of VW Hyi and other systems in quiescence.

6. Conclusions

We have carried a detailed study of the SU UMa system VW Hyi using *FUSE*. This is most intensive FUV study ever undertaken with a view to understanding the effect of an outburst on the WD in a nonmagnetic cataclysmic variable. In particular, we have observed the system from the end of a superoutburst all the way beyond the next normal outburst. Our main conclusions are as follows:

- The quiescent spectra are dominated by the WD, as anticipated, but also contain additional components. The WD is heated by the superoutburst to a temperature of 24,000 K and decays back to quiescence with a time constant of approximately 8 days; this confirms confirming the conclusions of Gänsicke & Beuermann (1996). The WD was not heated significantly by the normal outburst. It is rotating with $v \sin(i)$ of 420 km s^{-1} , and our abundance analysis confirms that the photosphere is deficient in C relative to N, again confirming earlier results obtained with *HST* that CNO processed material is being accreted onto the WD. The inferred abundance variations as a function of time from outburst are small, provided one allows for a second component in the FUV flux when fitting the data.
- There are phase-dependent FUV flux variations following the superoutburst, which last for at least 10 days beyond the end of the superoutburst. The strongest modulation 3 to 5 days after return to quiescence occurs on the superhump period, but later on the power in the orbital period is dominant, mimicking the behavior of the system at optical wavelengths during this period. The FUV flux peaks near phase 0.8, at the same phase where the hot spot is brightest at optical wavelengths; it therefore seems likely that the variable FUV flux component is associated with the hot spot. The FUV spectrum of the hot spot is relatively featureless and significantly hotter than either the optical hot spot or the WD in VW Hyi.
- The spectrum of VW Hyi also contains a third component in the FUV, which is seen clearly in the broadened emission lines associated with the disk. This third component appears during all phases of the quiescent observations and appears to have an associated "pseudo-continuum", which may be composed of large number of weaker lines or a true continuum. There is no compelling evidence for significant FUV emission from the boundary layer.

This analysis of *FUSE* data would not have been possible without the financial support from NASA through grant NNG04GQ38G. We appreciate this, as well as the dedicated efforts

of the entire *FUSE* team who spent the time and effort to make sure that the observations were a success. Janet A. Mattei of the AAVSO notified us that VW Hyi had undergone superoutburst and counseled us on when to schedule the observations; though others carry on admirably at the AAVSO, we miss her expertise, dedication, and friendship.

REFERENCES

- Armitage, P. J., & Livio, M. 1996, ApJ, 470, 1024
- Araujo-Betancor, S., et al. 2005, A&A, 430, 629
- Bergeron, P., Leggett, S. K., & Ruiz, M. T. 2001, ApJS, 133, 413
- Dixon, W. V., et al. 2007, PASP, 119, 527
- Gänsicke, B. T., & Beuermann, K. 1996, A&A, 309, L47
- Gänsicke, B. T., et al. 2003, ApJ, 594, 443
- Gänsicke, B. T., Szkody, P., Howell, S. B., & Sion, E. M. 2005, ApJ, 629, 451
- Godard, B. 2004, “IDF Cookbook”
- Godon, P., & Sion, E. M. 2005, MNRAS, 361, 809
- Hubble Space Telescope STIS Spectroscopy and Modeling of the Long-Term Cooling of WZ Sagittae following the 2001 July Outburst
- Godon, P., Sion, E. M., Cheng, F., Long, K. S., Gänsicke, B. T., & Szkody, P. 2006, ApJ, 642, 1018
- Godon, P., Sion, E. M., Cheng, F. H., Szkody, P., Long, K. S., & Froning, C. S. 2004, ApJ, 612, 429
- Hamada, T. & Salpeter, E. E. 1961, ApJ, 134, 683
- Harrison, T. E., Howell, S. B., Szkody, P., & Cordova, F. A. 2005a, ApJ, 632, L123
- Harrison, T. E., Johnson, J. J., McArthur, B. E., Benedict, G. F., Szkody, P., Howell, S. B., & Gelino, D. M. 2004, AJ, 127, 460
- Harrison, T. E., Osborne, H. L., & Howell, S. B. 2005b, AJ, 129, 2400
- Hubeny, I. 1988, Comput. Phys. Comm., 52, 103

- Hubeny, I. & Lanz, T. 1995, ApJ, 439, 875
- Knigge, C. 2006, MNRAS, 373, 484
- Ko, Y.-K., Lee, Y. P., Schlegel, E. M., & Kallman, T. R. 1996, ApJ, 457, 363
- Kromer, M., Nagel, T., & Werner, K. 2007, A&A, 475, 301
- Liu, F. K., Meyer, F., Meyer-Hofmeister, E., & Burwitz, V. 2008, A&A, 483, 231
- Long, K. S., Blair, W. P., Bowers, C. W., Davidsen, A. F., Kriss, G. A., Sion, E. M., & Hubeny, I. 1993, ApJ, 405, 327
- Long, K. S., Blair, W. P., Hubeny, I., & Raymond, J. C. 1996, ApJ, 466, 964
- Long, K. S., Brammer, G., & Froning, C. S. 2006, ApJ, 648, 541
- Long, K. S., Froning, C. S., Knigge, C., Blair, W. P., Kallman, T. R., & Ko, Y.-K. 2005, ApJ, 630, 511
- Marks, P. B., & Sarna, M. J. 1998, MNRAS, 301, 699
- Mauche, C. W., Lee, Y. P., & Kallman, T. R. 1997, ApJ, 477, 832
- Mennickent, R. E., Diaz, M. P., & Tappert, C. 2004, MNRAS, 347, 1180
- Merritt, J., Night, C., & Sion, E. M. 2007, PASP, 119, 251
- Meyer, F., Liu, B. F., & Meyer-Hofmeister, E. 2000, A&A, 361, 175
- Mineshige, S., Liu, B., Meyer, F., & Meyer-Hofmeister, E. 1998, PASJ, 50, L5
- Mohanty, P., & Schlegel, E. M. 1995, ApJ, 449, 330
- Moos, H. W., et al. 2000, ApJ, 538, L1
- Osaki, Y. 1989, PASJ, 41, 1005
- Paquette, C., Pelletier, C., Fontaine, G., & Michaud, G. 1986, ApJS, 61, 197
- Pandel, D., Córdova, F. A., & Howell, S. B. 2003, MNRAS, 346, 1231
- Patterson, J. 1998, PASP, 110, 1132
- Patterson, J., Richman, H., Kemp, J., & Mukai, K. 1998, PASP, 110, 403
- Polidan, R. S., Mauche, C. W., & Wade, R. A. 1990, ApJ, 356, 211

- Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 2007, Numerical Recipes: the Art of Scientific Computing, 3rd edn. (Cambridge: Cambridge U. Press), 807-818
- Piro, A. L., Arras, P., & Bildsten, L. 2005, ApJ, 628, 401
- Rogoziecki, P., & Schwarzenberg-Czerny, A. 2001, MNRAS, 323, 850
- Sahnow, D. J., et al. 2000, ApJ, 538, L7
- Schoembs, R., & Vogt, N. 1981, A&A, 97, 185
- Schreiber, M. R., Hameury, J.-M., & Lasota, J.-P. 2004, A&A, 427, 621
- Schwarzenberg-Czerny, A. 1996, ApJ, 460, L107
- Shaviv, G., & Wehrse, R. 1986, A&A, 159, L5
- Sion, E. M. 1995, ApJ, 438, 876
- Sion, E. M., Cheng, F. H., Gänsicke, B. T., & Szkody, P. 2004, ApJ, 614, L61
- Sion, E. M., Cheng, F. H., Sparks, W. M., Szkody, P., Huang, M., & Hubeny, I. 1997, ApJ, 480, L17
- Sion, E. M., Cheng, F.-H., Szkody, P., Gänsicke, B., Sparks, W. M., & Hubeny, I. 2001, ApJ, 561, L127
- Smith, A. J., Haswell, C. A., & Hynes, R. I. 2006, MNRAS, 369, 1537
- Tappert, C., Gänsicke, B. T., Schmidtobreick, L., Mennickent, R. E., & Navarrete, F. P. 2007, A&A, 475, 575
- Townsley, D. M., & Bildsten, L. 2003, ApJ, 596, L227
- van Amerongen, S., Damen, E., Groot, M., Kraakman, H., & van Paradijs, J. 1987, MNRAS, 225, 93
- van der Woerd, H., & Heise, J. 1987, MNRAS, 225, 141
- van der Woerd, H., van der Klis, M., van Paradijs, J., Beuermann, K., & Motch, C. 1988, ApJ, 330, 911
- Verbunt, F., Hassall, B. J. M., Pringle, J. E., Warner, B., & Marang, F. 1987, MNRAS, 225, 113

Vogt, N. 1983, A&A, 118, 95

Warner, B. 1987, MNRAS, 227, 23

Warner, B. 1995. Cataclysmic Variable Stars, Cambridge Astrophysics Series, Cambridge, New York: Cambridge University Press, pp 81-82

Williams, R. E. 1980, ApJ, 235, 939

Table 1. Observation Log

Obs. #	Dataset	Start Date (UT)	Start Time (days)	Time from T _o ^a (s)	Side 1 Exp. (s)	Side 2 Exp
1	E1140101	2004-07-30	14:52:02	-0.88	5939	5936 ^b
2	E1140102	2004-07-31	12:22:42	0.02	6320	6320
3	E1140103	2004-08-01	19:51:48	1.33	3212	3266
4	E1140104	2004-08-02	10:28:01	1.94	5558	5603
5	E1140105	2004-08-03	09:26:24	2.89	4809	4818
6	E1140106	2004-08-04	06:16:17	3.76	8378	8357
7	E1140107	2004-08-05	07:11:06	4.80	1100	6083
8	E1140108	2004-08-07	00:40:53	6.53	22754	22733
9	E1140109	2004-08-10	03:19:43	9.64	24018	24065
10	E1140110	2004-08-13	10:40:43	12.94	27160	26966
11	E1140111	2004-08-16	06:28:24	15.77	19496	19278 ^b
12	E1140112	2004-08-19	05:41:46	18.74	27254	26720
13	E1140113	2004-08-30	01:08:05	29.55	21916	21894

^aT_o is time from JD2453218.0, see text.

^bOutburst spectrum.

Table 2. Scaled Abundance WD - Power Law Fits

Obs. #	Norm. (10 ⁻²³)	T _{wd} (1000 K)	z	v sin(i) (km s ⁻¹)	f(1000 Å) ^a	α	χ _ν ²
2	21.9±1.9	24.3±0.2	3.3±1.0	530±170	10.3±0.4	2.2±1.0	3.6
3	21.9±2.2	23.3±0.3	2.1±0.6	430±190	3.8±0.2	3.1±1.4	2.1
4	22.1±1.6	23.1±0.2	2.6±0.8	450±150	5.1±0.2	3.3±1.0	2.9
5	21.4±2.0	22.4±0.2	1.9±0.6	420±240	3.2±0.2	2.5±1.3	2.4
6	20.7±2.2	22.3±0.2	1.8±0.6	360±220	3.2±0.2	2.5±1.4	3.0
7	19.5±1.9	22.0±0.2	2.2±0.8	450±190	2.5±0.2	3.8±1.6	1.7
8	18.4±2.5	22.0±0.3	1.8±0.7	360±230	3.3±0.1	3.1±1.0	5.8
8 (high)	16.9±2.5	22.6±0.3	2.1±0.7	430±200	5.0±0.2	4.1±0.8	2.6
8 (low)	19.7±1.7	21.4±0.2	1.6±0.5	350±200	1.1±0.1	6.0±2.3	3.1
9	17.8±2.1	21.2±0.2	1.4±0.5	360±230	2.1±0.1	3.1±1.2	5.5
9 (high)	15.7±1.6	22.0±0.3	1.5±0.4	360±160	3.7±0.2	3.1±0.8	1.9
9 (low)	18.6±2.3	20.9±0.2	1.4±0.5	350±260	0.8±0.1	5.5±2.1	3.6
10	17.0±1.9	20.8±0.2	1.3±0.5	350±190	1.2±0.1	3.6±1.9	5.6
12	18.1±2.6	20.6±0.3	1.3±0.6	360±240	1.7±0.1	2.5±1.6	6.1
13	15.4±2.2	19.5±0.2	0.8±0.5	320±280	0.9±0.1	2.1±2.1	4.2

^af(1000) Å is in units of 10⁻¹⁴ ergs cm⁻² s⁻¹ Å⁻¹

Table 3. Variable Abundance WD - Power Law Fits

. #	Norm. (10^{-23})	T_{wd} (1000 K)	C	N	Si	S	$v \sin(i)$ (km s $^{-1}$)	f(1000 Å) ^a	α	χ^2_ν
2	21.6±1.4	24.1±0.2	0.8±0.2	6.4±2.2	4.4±1.0	2.8±0.5	570±30	10.4±0.3	1.5±0.7	3.2
3	22.4±1.3	23.0±0.2	0.6±0.2	5.7±2.2	2.8±0.5	1.3±0.5	460±30	3.9±0.2	2.5±1.1	1.9
4	22.7±1.4	22.8±0.2	0.6±0.2	6.9±2.2	3.8±0.8	1.8±0.6	490±30	5.2±0.3	2.5±0.9	2.5
5	22.7±1.2	22.1±0.2	0.5±0.2	5.8±1.7	3.4±0.8	1.2±0.4	450±20	3.4±0.2	2.2±1.1	2.0
6	21.6±1.2	22.0±0.2	0.5±0.2	4.6±1.9	2.8±0.5	1.1±0.3	410±20	3.3±0.1	2.2±0.9	2.5
7	20.4±1.4	21.6±0.2	0.5±0.3	4.4±1.6	3.4±0.9	2.2±0.7	490±30	2.6±0.1	3.1±0.9	1.5
8	19.7±1.3	21.6±0.2	0.5±0.2	4.0±2.1	2.7±0.4	1.0±0.3	410±30	3.4±0.1	2.2±0.9	4.8
8 (high)	17.6±1.3	22.3±0.3	0.7±0.2	5.8±2.4	2.7±0.7	1.3±0.4	470±40	5.0±0.2	3.4±0.6	2.5
8 (low)	21.5±1.0	21.1±0.1	0.5±0.2	4.8±1.7	2.8±0.4	1.0±0.2	400±20	1.2±0.1	4.3±1.5	2.4
9	19.9±1.2	20.8±0.2	0.4±0.2	4.9±2.0	2.7±0.4	1.0±0.2	410±30	2.2±0.1	2.5±0.9	4.0
9 (high)	18.0±1.3	21.5±0.2	0.6±0.2	6.6±2.2	2.4±0.4	1.0±0.3	440±40	3.8±0.2	2.5±0.8	1.7
9 (low)	21.5±1.1	20.4±0.2	0.4±0.2	5.4±1.9	2.8±0.5	1.0±0.1	410±30	0.9±0.1	4.6±1.4	2.5
10	20.1±1.1	20.3±0.1	0.5±0.2	6.0±2.2	2.7±0.4	1.0±0.2	420±40	1.3±0.1	2.5±1.3	4.0
12	21.0±1.3	20.2±0.2	0.4±0.2	5.8±2.2	2.7±0.3	1.0±0.3	440±30	1.8±0.1	2.2±1.0	4.5
13	19.4±1.3	19.0±0.2	0.4±0.2	6.1±2.2	2.5±0.6	1.0±0.1	410±30	0.9±0.1	2.1±1.3	3.2

^af(1000) Å is in units of 10^{-14} ergs cm $^{-2}$ s $^{-1}$ Å $^{-1}$

Fig. 1.— Optical and ultraviolet light curves of VW Hyi obtained throughout August 2004. Time-resolved ground-based observations are shown in black (a–n), *FUSE* observations in blue (01–13), and observations from the AAVSO data base in red (filled circles are detections, open circles are upper limits).

Fig. 2.— The time-averaged spectra obtained during Obs. 1, 2, 8, and 13. All of the spectra have been scaled so that the flux at 1100 Å is at about the same relative position each frame. The flux observed from VW Hyi declined steadily after the superoutburst, until Obs. 11 when the source was observed near the end of a normal outburst. The Obs. 11 spectrum was essentially identical to that observed in Obs. 1. By Obs. 13, the flux had declined to a level below that observed in Obs. 10. The character of the spectrum obtained at the end of the super-outburst is quite different from the spectra observed when the system was in optical quiescence. It has a narrower Lyman β profile and far fewer deep absorption features in the wavelength range between 1050 and 1160 Å. The outburst spectra show O VI $\lambda\lambda 1032, 1038$ in absorption whereas the quiescent spectra all show it in emission. All of the spectra, including those in quiescence, show emission extending to the Lyman limit, although the relative intensity of emission at the shortest wavelengths declines with time from outburst. The narrow emission lines which appear in the spectra are all airglow lines.

Fig. 3.— Time-series analysis of the optical data, power spectra on the left, and phase-folded light curves on the right. P_{orb} and P_{sh} indicate the orbital and superhump period, respectively. From top to bottom: (a) analysis of combined optical observations b–h (see Fig. 1). The light curve is folded on the period corresponding to maximum power, the zero-point in phase is arbitrary. (b) same as top panel, but after removing the superhump signal. The light curve is folded on the ephemeris in Eq.(1). (c) same as top panel, but after removing the orbital signal. The light curve is folded on the superhump period, the zero-point in phase is arbitrary. (d) power spectrum and phase-folded light curve for the combined optical observations j–n, the light curve is folded on the ephemeris of van Amerongen et al. (1987).

Fig. 4.— Time-series analysis of the *FUSE* data. P_{orb} and P_{sh} indicate the orbital and superhump period, respectively. (a) analysis of the combined observations 03–05 (see Fig. 1). The light curve is folded on the superhump period, the zero-point in phase is arbitrary. (b) analysis of the combined observations 08–10, the light curve is folded on the ephemeris in Eq. (1).

Fig. 5.— The average flux from VW Hyi measured as a function of time in Obs. 8 and 9. The flux is obtained from spectra extracted in 1 minute intervals, ignoring regions where airglow is likely to appear. Time is measured in periods from a fiducial time prior to the

first observation of VW Hyi. Integral periods correspond to secondary conjunction, which occurs 0.15 periods after phase 0 in the ephemeris of van Amerongen et al. (1987). The gaps are times without data, often due to earth blockage. The observed flux is preferentially high just prior to secondary conjunction, near phase 0.8, that is near hot spot maximum

Fig. 6.— Spectra of VW Hyi from Obs. 8 and 9 in black and red, respectively. The upper panel shows the “high flux” spectrum during orbital phase 0.625-1.0 when the overall flux was highest. The middle panel shows the “low flux” spectrum from phases 0.0 to 0.375 when the flux was low. The lower panel shows the difference spectrum. Note that the vertical scale for the panel showing the difference spectrum is not the same as for the other two panels. All of the spectra have been box-car smoothed to a resolution of about 0.5 Å.

Fig. 7.— A comparison of two model fits to the time-averaged spectrum of Obs. 8. In both cases a log g=8 WD - models were fit to the data. In the upper panel, only the overall metal abundance was varied while in the lower panel the individual abundances of C, N, Si and S were varied, and all other species were set to 1. The data are plotted in black if this portion of the data was used in the fit and in grey if the data were excluded from the fit. The best fitting model is plotted in blue. The power-law contribution to the total spectrum is shown in red in the lower panel.

Fig. 8.— Log g=8 WD - power law fits to the time-averaged spectra from Obs. 2 and 13. In both cases, the abundances of C, N, Si and S were allowed to vary independently. The color conventions are the same as in Fig. 7.

Fig. 9.— Log g=8 WD - power law fits to the high (upper panel) and low (lower panel) flux spectra obtained of VW Hyi in Obs. 8. The abundances are allowed to vary in both cases. The color conventions are the same as in Fig. 7.

Fig. 10.— A summary of trends in T_{wd} (upper left), $v \sin(i)$ (upper right), R_{wd} (lower left), and the $F_\lambda(1000 \text{ \AA})$ flux from the second component (lower right) as a function of time from superoutburst when fitting the data as a WD with variable abundances and a power law. The black, blue and red curves correspond to log g=7.5, 8.0, and 8.5 models respectively. The dotted horizontal lines in the lower left hand panel correspond from top to bottom the expected radius for a log g=7.5, 8.0 and 8.5 WD, based on the models of Bergeron et al. (2001) for a 20,000K WD.

Fig. 11.— The radius of the WD in VW Hyi as measured from fits to log g=7.5, 8.0 and 8.5 variable abundance models assuming a distance of 65 pc. Only fits after day 5 are shown. Mass radius relations for a cold (Hamada & Salpeter 1961) and 20,000K (Bergeron et al. 2001) WD are shown as the dashed black and solid red curves, respectively. The comparison

suggests a somewhat higher mass or somewhat greater distance for VW Hyi than is commonly assumed.

Fig. 12.— Comparisons of the best fitting BB (upper panel) and log g=4 stellar models to the “hotspot” spectrum as measured in Obs. 8.

Fig. 13.— A comparisons between the non-WD components of the Obs. 8 “low flux” (top panel) and Obs. 13 time-averaged (bottom panel) spectra to the “hot spot” spectrum obtained in Obs. 8. All of the spectra have been box-car smoothed to a resolution of about 1 Å. The very narrow emission features in the upper and low panel are all air-glow lines, and the same lines occasionally manifest themselves as narrow absorption profiles in the hot spot spectrum.

Fig. 14.— The luminosity (plotted in red) of the WD as a function of time from outburst as calculated from the log g=8 variable abundance plus power law fits. The black lines are for models with exponential decays of 5, 7 and 9 days. The data point which falls above all 3 exponential curves was for the observation that occurred just after the normal outburst of VW Hyi



























